# STRENGTH OF THIN INTERMEDIATE LAYERS

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16. Abstract

The mechanical properties of thin ferrosilicon layers sandwiched between plates of a high-strength martensitic steel (30KhGSA) and between plates of a mild steel (Steel-3) are studied at temperatures ranging between 20 and 1000°C, using cylindrical samples. The tensile strength of the samples is plotted vs. the relative thickness of the ferrosilicon layer.

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STRENGTH OF THIN INTERMEDIATE LAYERS

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It has been shown in a number of works [1-6] that the onset of plastic deformation in a thin, soft, intermediate layer, located between two solid supports, is hampered and that its stress state acquires a three-dimensional nature. In this case, an increase in the strength and yield point of the intermediate layer is observed; the less the ratio of intermediate layer thickness to diameter of the contact surface and the greater the difference in the yield points of the base metal and the metal of the intermediate layer, the greater it is. /111*

Expressions of the mean values of the normal stresses, corresponding to the limiting state and characterizing the carrying capacity of the intermediate layer, have been found by a number of authors [3-6]:

$$P = \sigma_t^m\left(1 + \frac{1}{3\sqrt{3}\chi}\right); \tag{1}$$

$$P_* = \sigma_t^m\left(\frac{\pi}{4} + \frac{1}{3\sqrt{3}\chi}\right). \tag{2}$$

where P and $P_*$ are the mean stresses, corresponding to the limiting state of the intermediate layer; $\sigma_t^m$ is the yield point of the intermediate layer material; and $\chi$ is its relative thickness, $\chi = h/d$.

Formula (1) was obtained by analysis of the limiting stress state only at the contact surfaces of the intermediate layer and (2), over the entire volume of the intermediate layer.

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*Numbers in the margin indicate pagination in the foreign text.

The calculation formulas (1) and (2) presented are more precisely defined in work [4], for the cases when the effect of physical hardening of the metal of the intermediate layer during its employment in a welding compound cannot be disregarded:

$$P^{*} = \sigma_b^m \left[ 1 + \frac{1}{3\sqrt{3}\chi (1+\varepsilon_b)^{3/2}} \right]. \qquad (3)$$

where $\sigma_b^m$ is the strength of the intermediate layer material; /112
$\varepsilon_b$ is the relative lengthening of the intermediate layer, corresponding to its strength in the free state.

This work presents the results of investigation of the properties of thin ferrosilicon intermediate layers, located between two supports of high-strength martensitic Steel A (30KhGSA), as well as of the properties of the intermediate layer between supports of Steel 3, over a broad temperature range (20-1000°C). The choice of composition of the materials for study of the intermediate layer properties proceeded from the following principles: the materials should not form brittle compounds between themselves and they should differ considerably in strength and yield point. The characteristics of the initial materials at a temperature of 20°C are presented in Table 1.

TABLE 1.

| Materials | $\sigma_b$ kg/mm$^2$ | $\sigma_{0.2}$ kg/mm$^2$ | $\delta$, % | $\psi$, % |
|---|---|---|---|---|
| Martensitic steel A | 145-150 | 124 | 12-14 | 30-35 |
| Ferrosilicon ($Fe_{Si}$) | 52.5 | 38 | 31-35 | 50-55 |
| Steel 3 | 41.5 | 25 | 41-50 | 50-55 |

The compositions Steel A - $Fe_{Si}$ - Steel A and Steel 3 - $Fe_{Si}$ - Steel 3 were produced by means of heating and rolling packs, at a temperature of 1000°C in vacuum [7, 8], in one pass with 25% reduction; this ensured a high, uniform binding strength of the components of the pack.

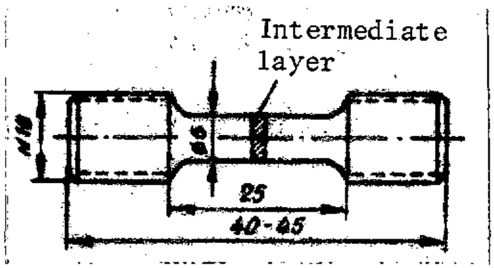


Fig. 1. Shape and dimensions of samples for testing mechanical properties.

The mechanical properties of the compositions were determined on cylindrical samples (Fig. 1), cut across the height of the pack, so that the ferrosilicon intermediate layer was in the middle portion of the sample. The tests were carried out on a UM-5 type vacuum tensile-testing machine, with a clamp movement rate of 0.2 mm/min. The samples of the initial materials and compositions were annealed in a vacuum of $2 \cdot 10^{-5}$ mmHg, at a temperature of 1000°C, for a period of 1 h, before the tests.

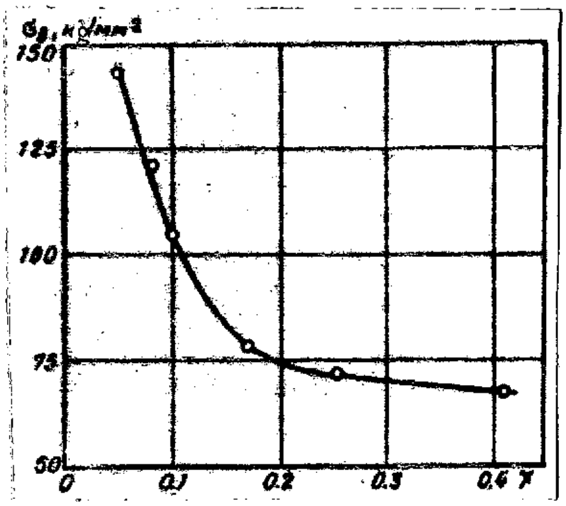


Fig. 2. Composition Steel A - $Fe_{Si}$ - Steel A sample strength vs. relative thickness of $Fe_{Si}$ intermediate layer.

Steel A - $Fe_{Si}$ - Steel A sample strengths vs. relative thickness ($\chi$ = h/d) of the $Fe_{Si}$ intermediate layer are presented in Fig. 2. The different $\chi$ values were obtained by way of change in thickness of the intermediate layer. Breaking of the samples took place across the ferrosilicon (Fig. 3a, b); therefore, under these experimental conditions, the strength of the composition /113

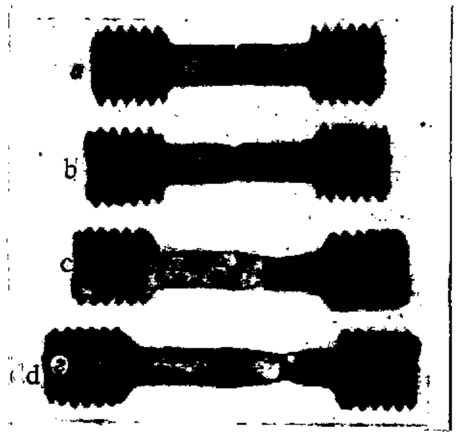

Fig. 3. Nature of breaking of specimens of compositions Steel A - $Fe_{Si}$ - Steel A (a, b) and Steel 3 - $Fe_{Si}$ - Steel 3 (c, d).

was determined by the strength of the intermediate layer.

As follows from Fig. 2, with a relative intermediate layer thickness $\chi$ = 0.4-0.5, the strength of the composition is 15-20% higher than the strength of samples of the initial ferrosilicon. With decrease in relative intermediate layer thickness from 0.3 to 0.05, the breaking stress increases according to a hyperbolic function and, at $\chi$ = 0.05, reaches a value 2.7 times greater than in monolithic ferrosilicon samples.

The breaking of samples with a relative intermediate layer thickness $\chi > 0.35$ is of a viscous nature, and at $\chi < 0.25$, brittle rupture takes place.

A comparison was made of the experimental data on intermediate layer strength with the calculated (Table 2), obtained by formulas (1)-(3). In the case of brittle rupture of samples ($\chi$ = 0.08-0.25), the greatest concordance with experimental data is observed for the calculation by formula (2), and in viscous rupture ($\chi > 0.35$), by formula (3). Deviations of the calculated data from the experimental can be explained by structural peculiarities of the intermediate layer material, which are not taken into account by formulas (1)-(3).

TABLE 2.

| h, mm | x | $\sigma_b$ Experimental Values kg/mm² | Calculated Data: P, kg/mm² | Difference % | $P_*$, kg/mm² | Difference % | $P^*$, kg/mm² | Difference % |
|---|---|---|---|---|---|---|---|---|
| 0.41 | 0,082 | 121,0 | 126,9 | +4,5 | 118,7 | −2,0 | 167,0 | +27.5 |
| 0.50 | 0,10 | 106,6 | 110,9 | +3,0 | 102,8 | −4.0 | 147.0 | +28.0 |
| 0.84 | 0,168 | 74,6 | 81,4 | +8,5 | 73,1 | −2,0 | 108.0 | +31,0 |
| 1,24 | 0,248 | 73,6 | 67,4 | −8,5 | 59,2 | −24.0 | 89,5 | +17,5 |
| 2,03 | 0,406 | 67,6 | 55,9 | −17,0 | 47,7 | −41,5 | 75,0 | +10,0 |

The results of temperature tests of Steel A samples (curve 1), ferrosilicon (curve 4) and the composition Steel A - $Fe_{Si}$ - Steel A, with relative intermediate layer thickness of 0.08 (curve 2) and 0.25 (curve 3), are presented in Fig. 4. Rupture of samples at all test temperatures took place across the intermediate layer.

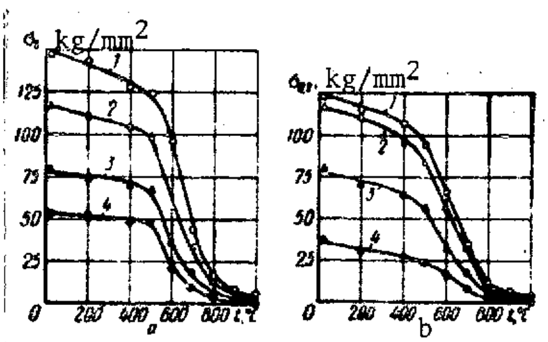


Fig. 4. Strengths (a) and yield points (b) of materials vs. test temperatures.

The strength of ferrosilicon in the intermediate layer, at temperatures of 20-500°C (see Fig. 4, curve 2), is 2-2.3 times greater than the strength of monolithic $Fe_{Si}$ samples. With increase in test temperature, the strength of the intermediate layer in the composition increases still more. Thus, at test temperatures of 900-1000°C, the intermediate layer strength is 4-5 times greater than the strength of monolithic ferrosilicon samples at these same temperatures. Similar changes in test temperatures are observed for the yield point of the intermediate layer (see Fig. 4 b).

Thus, with increase in temperature, the effect of contact hardening of thin intermediate layers of pliable metals does not disappear, but increases to a still greater extent. This can be explained by increase in the difference in the strength characteristics of the basic material (Steel A) and the intermediate layer materials, which is one of the primary factors [3-5] affecting the degree of rigidity of the three-dimensional stress state of thin intermediate layers of pliable metals.

In distinction from the stress state of soft intermediate layers, such hard ones become "softer" during deformation than under conditions of uniaxial stretching of monolithic samples of the intermediate layer material [5]. Plastic deformation in the near-contact region of a solid intermediate layer (and in thin ones, the entire volume) can begin at medium stresses, with knowledge of the lesser yield points $\sigma_{0.2}$ of its material /114
in uniaxial stretching. This phenomenon was called the "softening effect" in work [5].

The composition Steel 3 - $Fe_{Si}$ - Steel 3 was used to show the softening effect, where the ferrosilicon intermediate layer of various thicknesses emerges as the hard layer. In tests of this composition, sample rupture always took place through the Steel 3 (see Fig. 3, c, d).

The research showed that intermediate layers with a relative thickness $\chi$ = 0.076-0.4 proved to be involved in a noticeable plastic deformation at stresses amounting to 0.88-0.95 $\sigma_{0.2}$ of the initial ferrosilicon.

Let us examine the relation of the relative lengthening of the hard intermediate layer to its relative thickness (Fig. 5). Stresses which caused residual plastic deformations in the hard intermediate layer were equal to the breaking point of the

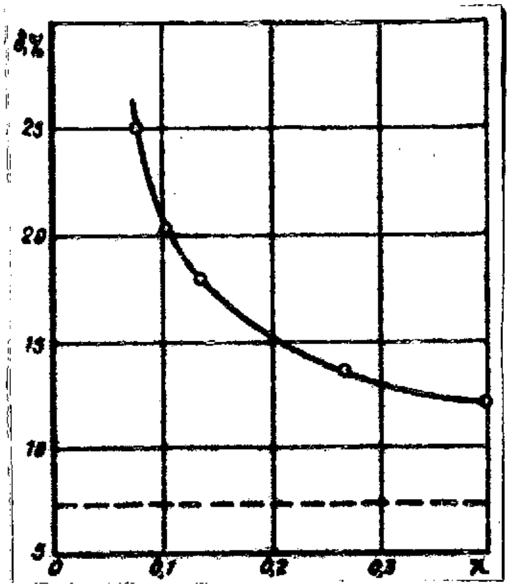


Fig. 5. Relative lengthening of $Fe_{Si}$ intermediate layers in composition Steel 3 - $Fe_{Si}$ - Steel 3 vs. its relative thickness.

Steel 3 - $Fe_{Si}$ - Steel 3 composition, i.e., they are determined by the strength of the basic metal (Steel 3).

In comparison of the residual deformations in the intermediate layer with deformations found from the stretching diagrams of samples of the initial ferro-silicon at the same stresses, it is clear that deformations in the intermediate layer considerably exceed those of the initial metal and depend on the relative thickness of the intermediate layer (see Fig. 5). Thus, for example, in intermediate layers with a relative thickness of 0.27 and 0.076, the quantity $\delta$ amounts to 13.5 and 25%, respectively, at $\sigma_b$ = 42 kg/mm$^2$, while in the initial ferro-silicon, $\delta$ = 7.2% at the same stress (dashed line).

In uniaxial stretching of samples with a transverse hard intermediate layer, the material becomes softer. Examinations of the microstructure and microhardness of the intermediate layer confirmed the softening effect. For example, if the microhardness of the intermediate layer is identical over the entire thickness of the initial samples ($H_\mu^{in}$ = 201-214 kg/mm$^2$), in ruptured samples with an intermediate layer thickness h = = 2.05 mm, the microhardness $H_\mu$ = 201-207 kg/mm$^2$ in the middle portion, 221-232 kg/mm$^2$ at the boundaries of the section; for an intermediate layer with h = 0.67 mm, $H_\mu$ = 221-232 kg/mm$^2$ in the middle portion and 244 kg/mm$^2$ at the boundaries of the section; for an intermediate layer of h = 0.38 mm, the microhardness of the intermediate layer is identical through the entire thickness and amounts to 307-316 kg/mm$^2$.

The increase in microhardness at the boundaries of the section, in comparison with that of the middle portion, for the intermediate layer with h = 2.05 mm, is explained by localization of plastic deformation in the near-contact region. The identical microhardness ($H_\mu > H_\mu^{in}$ over the entire thickness of the intermediate layer (h = 0.38 mm) is evidence of involvement of the entire volume of the hard metal in plastic deformation at stresses less than its yield point.

Thus, the properties of the intermediate layer in a composition are determined by the peculiarities of its stress state. Study of the behavior of thin intermediate layers permits the properties of the composition as a whole to be predicted to a certain extent.

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